



# Demonstration of Stereo Vision For Deorbit Descent and Landing

*42<sup>nd</sup> Annual AAS Guidance and Control Conference, Session III, February 3<sup>rd</sup>, 2019*

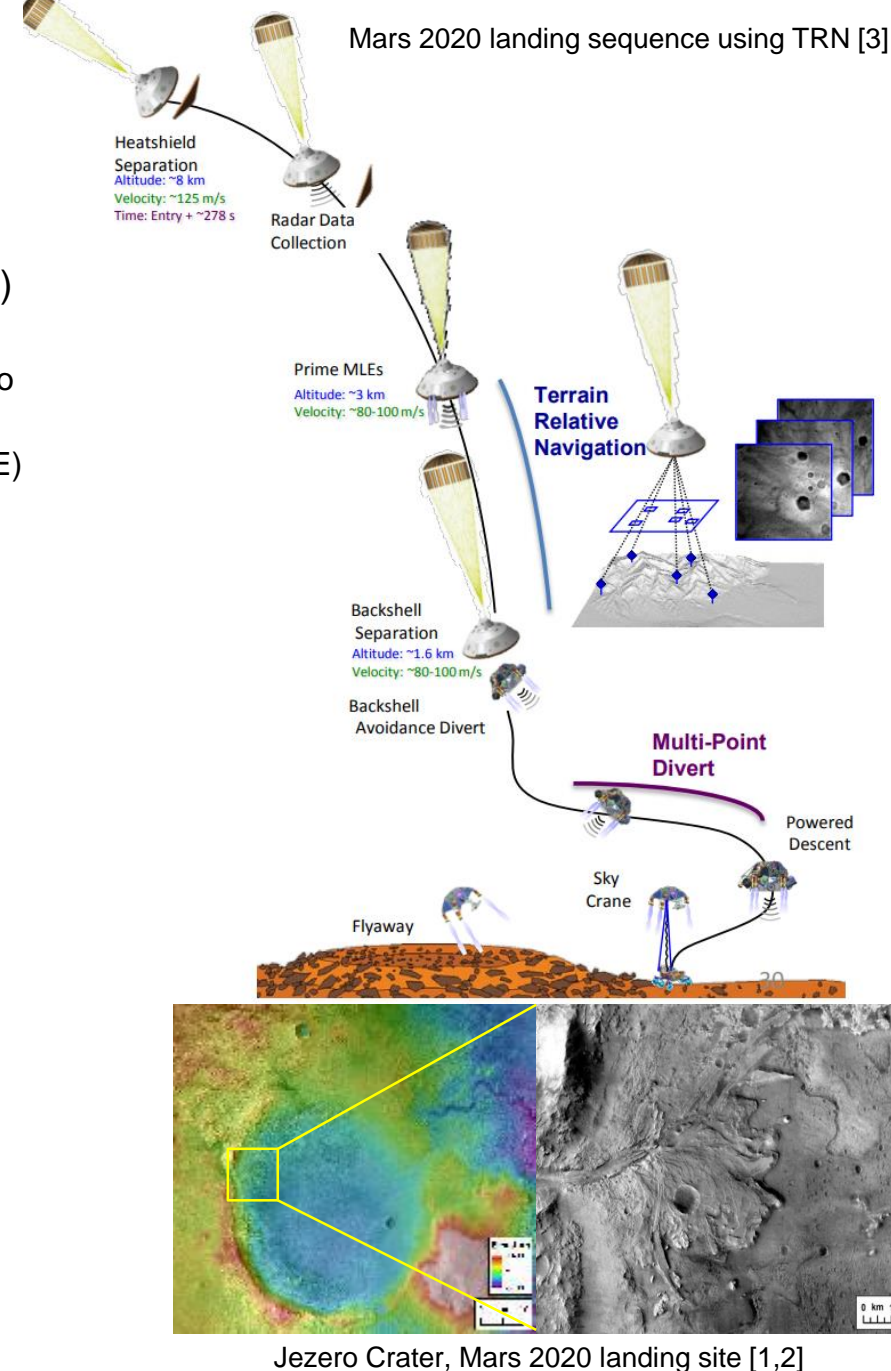
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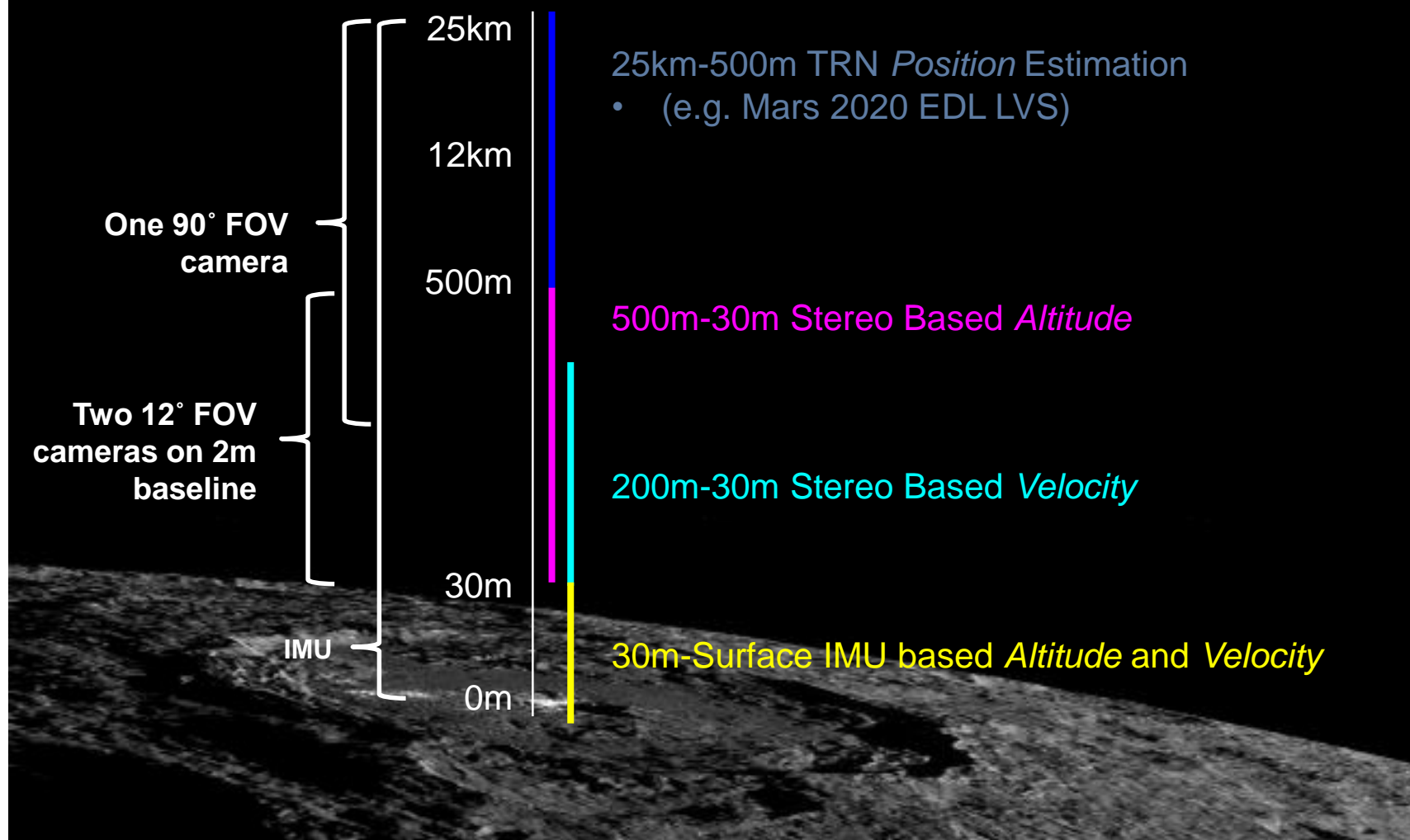
# Motivation

- Vision sensors for entry, descent, and landing (EDL) provide benefits with minimal added mass
  - E.g. vision-based Terrain Relative Navigation (TRN)
    - Critical for selection of Mars 2020 landing site [1]
    - Matches images with map for localization at ~4.2 km to ~2 km
    - Uses high performance Vision Compute Element (VCE)
- During powered descent, soft landers need to remove residual velocity at low altitude
  - *Altitude* and *velocity* need to be sensed
  - Commonly (i.e. Mars 2020) a combination of IMU and **radar** are used for this
- **Radar** is typically either:
  - Expensive and heavy with excellent performance
  - Inexpensive and lightweight with poor performance
- Wide-baseline stereo vision could provide an inexpensive and lightweight alternative *altitude* and *velocity* sensor for future missions
  - Requires only addition of 2× stereo cameras
  - For slow-moderate descent rates, could use capabilities of existing VCE for image processing



# Proposed Concept of Operations

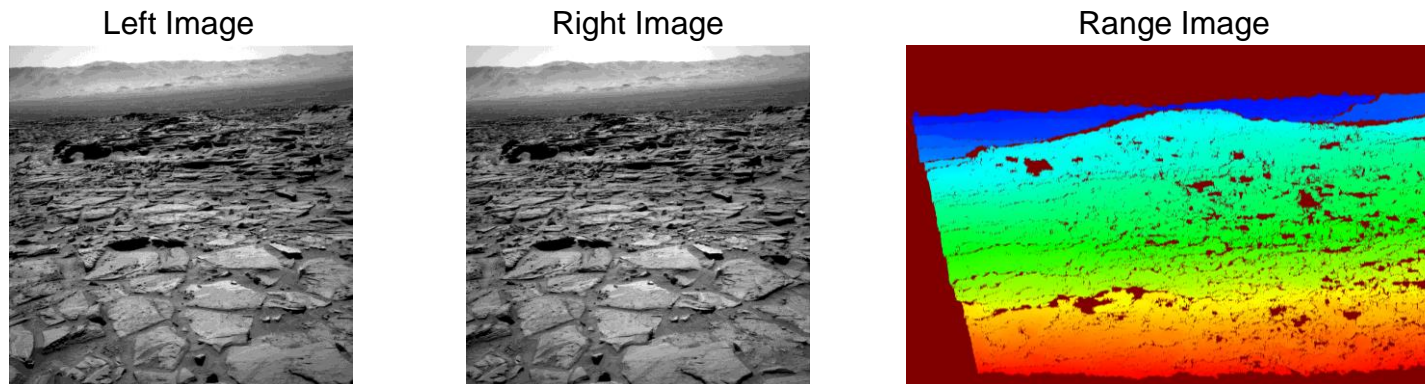
## Notional Sensor Operation



TRN	Terrain relative navigation	EDL	Entry, descent, and landing	IMU	Inertial measurement unit
FOV	Field of view	LVS	Lander vision system		

# Knowledge Gap

- Stereo vision
  - Proven for rover operations at  $< 15$  m range and oblique viewpoint



- Theoretical performance adequate for entry, descent and landing (EDL)
- EDL-level performance not proven
- Controlled tests are required to verify that stereo vision can be used in practice for EDL at ranges up to 500 m
  - Verify stereo vision accuracy
  - Verify stereo vision feasibility in flight-like scenario
  - Verify visual odometry accuracy
  - Verify stereo precision meets theoretical performance

Ground test

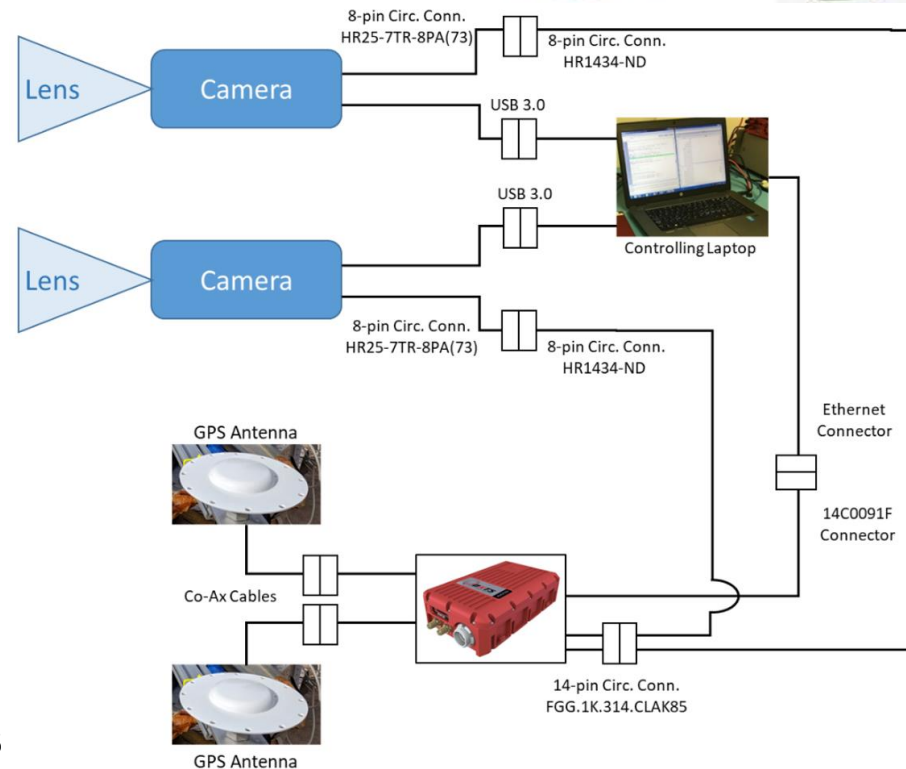
Flight test

Flight test

Flight test

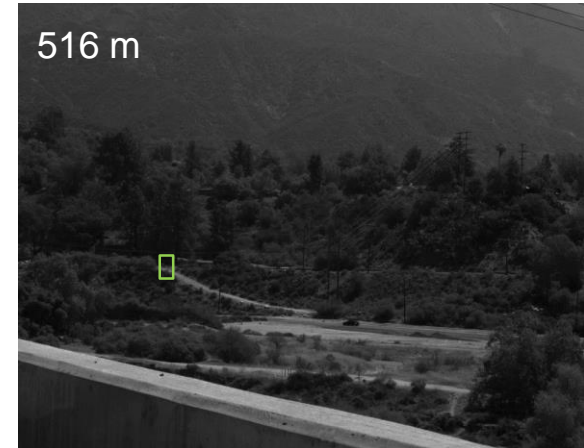
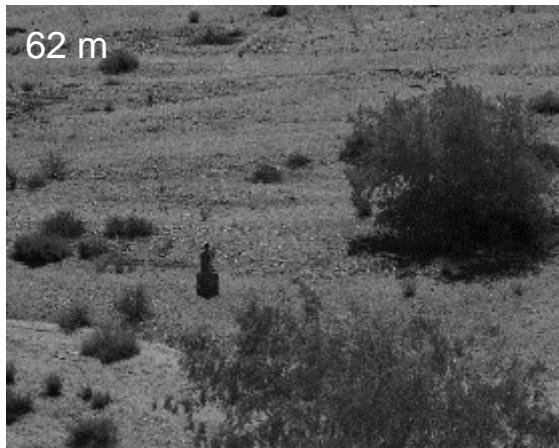
# Test Hardware and Software

- Stereo cameras
  - 2x IDS UI-3180CP-M-GL with USB 3.0 interface
  - Python 5000 detector (2/3", 2592x2048, CMOS)
    - Same as Mars 2020 LVS camera (LCAM)
- Lenses
  - 2x Schneider Xenon-Topaz 2.0/38mm
  - 18.6° horizontal field of view
- Ground truth pose sensor
  - xNav 550 GNSS/INS
  - 2x GPS antennas
- Ground truth range sensor
  - Leica Total Station
- Data collection (images)
  - Laptop running StreamPix 7
- Data collection (ground truth)
  - Onboard xNav550
  - Post-processing with RT Post-Process



# Ground Test Overview

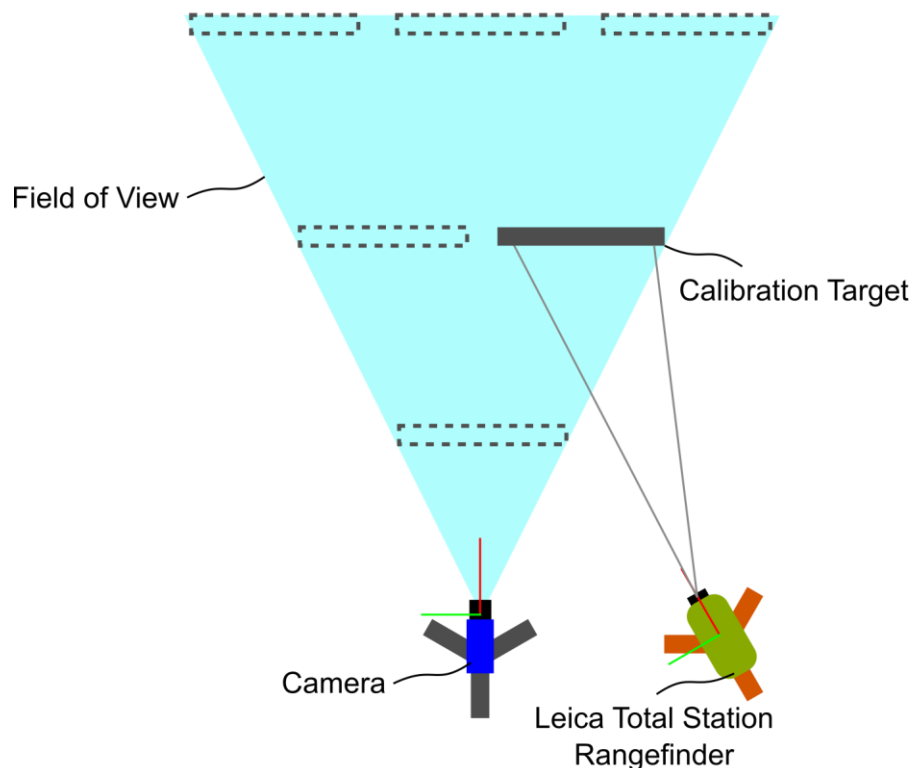
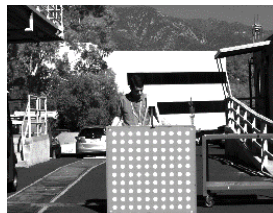
- Cameras mounted coaxially at 2 m baseline on 80/20 Aluminum bar
- Positioned atop JPL parking structure overlooking the Arroyo Seco
- Images taken of textured patch at ranges between 62 and 516 m
- Leica Total Station measured retroreflector distance (co-located with patch)



# Ground Test Calibration

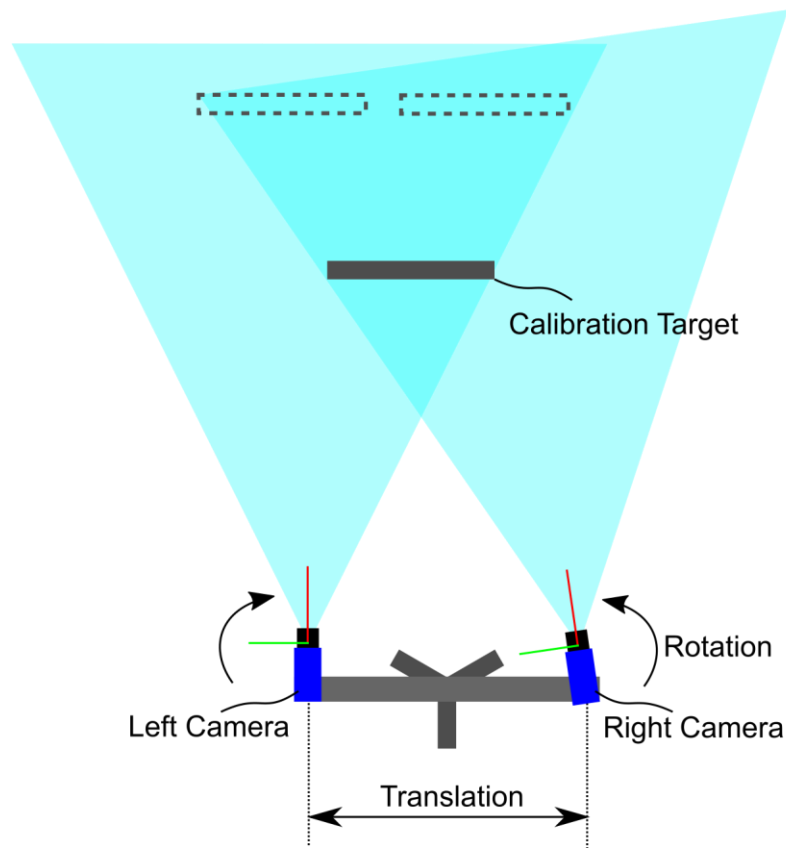
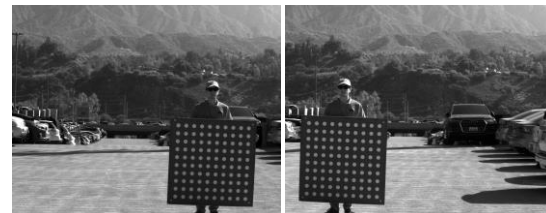
## *Intrinsic Calibration (Monocular)*

- Internal camera parameters such as focal length and distortion



## *Extrinsic Calibration (Stereo)*

- Translation and rotation between left and right camera

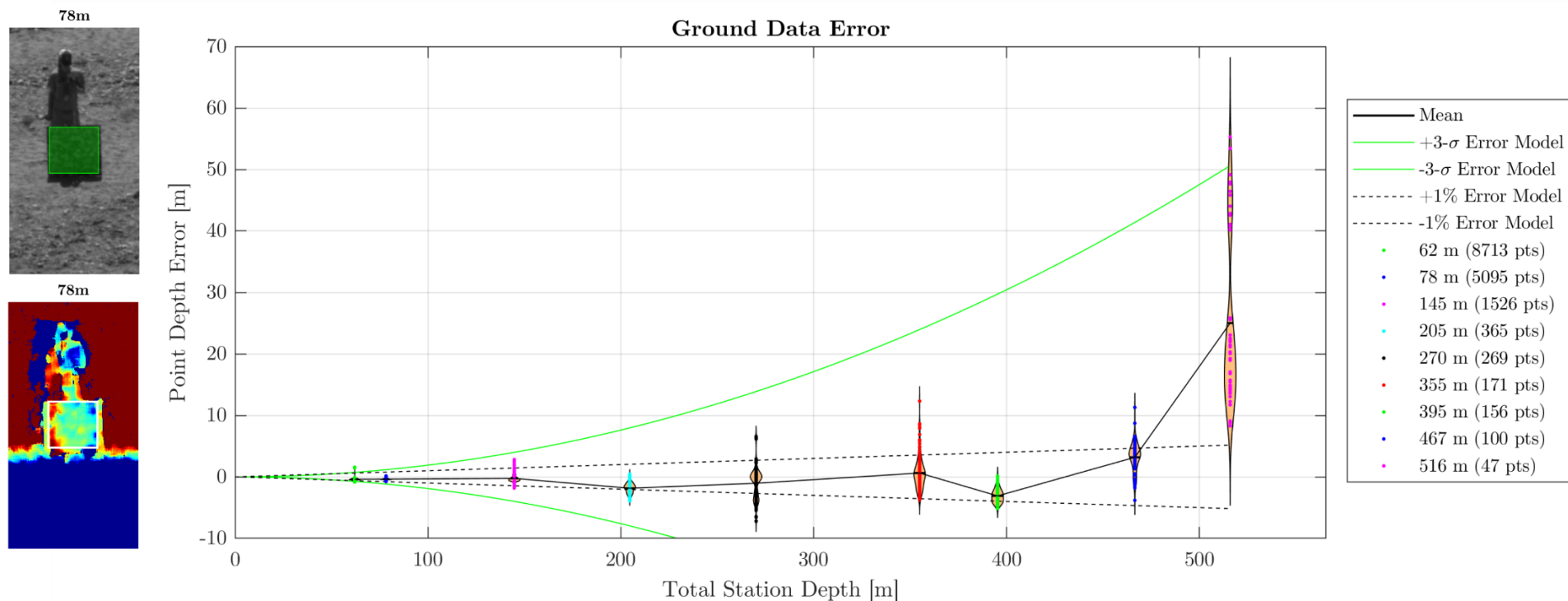


# Ground Test Results

- Dense depth map extracted
- Texture patch position located in rectified images (and depth map)

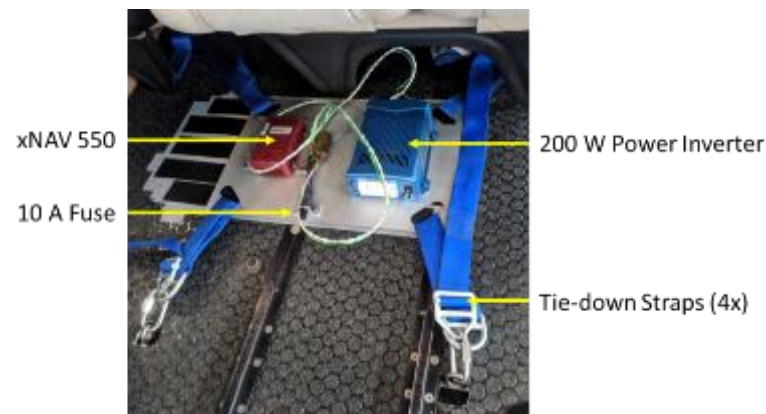
Measured Depth (LTS)	# of Points in Patch	Mean Stereo Depth Error	3- $\sigma$ Stereo Depth Error
62.034 m	8713	-0.385 m (0.620 %)	0.372 m (0.599 %)
78.297 m	5095	-0.371 m (0.474 %)	0.417 m (0.533 %)
144.774 m	1526	-0.246 m (0.170 %)	1.568 m (1.083 %)
204.670 m	365	-1.848 m (0.903 %)	2.422 m (1.184 %)
270.170 m	269	-1.037 m (0.384 %)	7.016 m (2.597 %)
354.953 m	171	0.624 m (0.176 %)	7.745 m (2.182 %)
395.379 m	156	-3.097 m (0.783 %)	3.266 m (0.826 %)
466.546 m	100	3.181 m (0.682 %)	7.087 m (1.519 %)
515.977 m	47	25.023 m (4.850 %)	41.636 m (8.069 %)

< 1% patch mean range error below 500 m



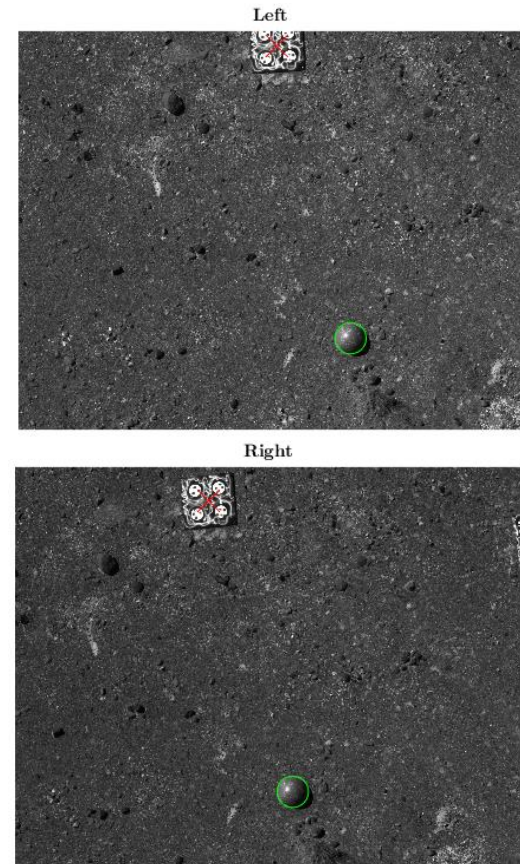
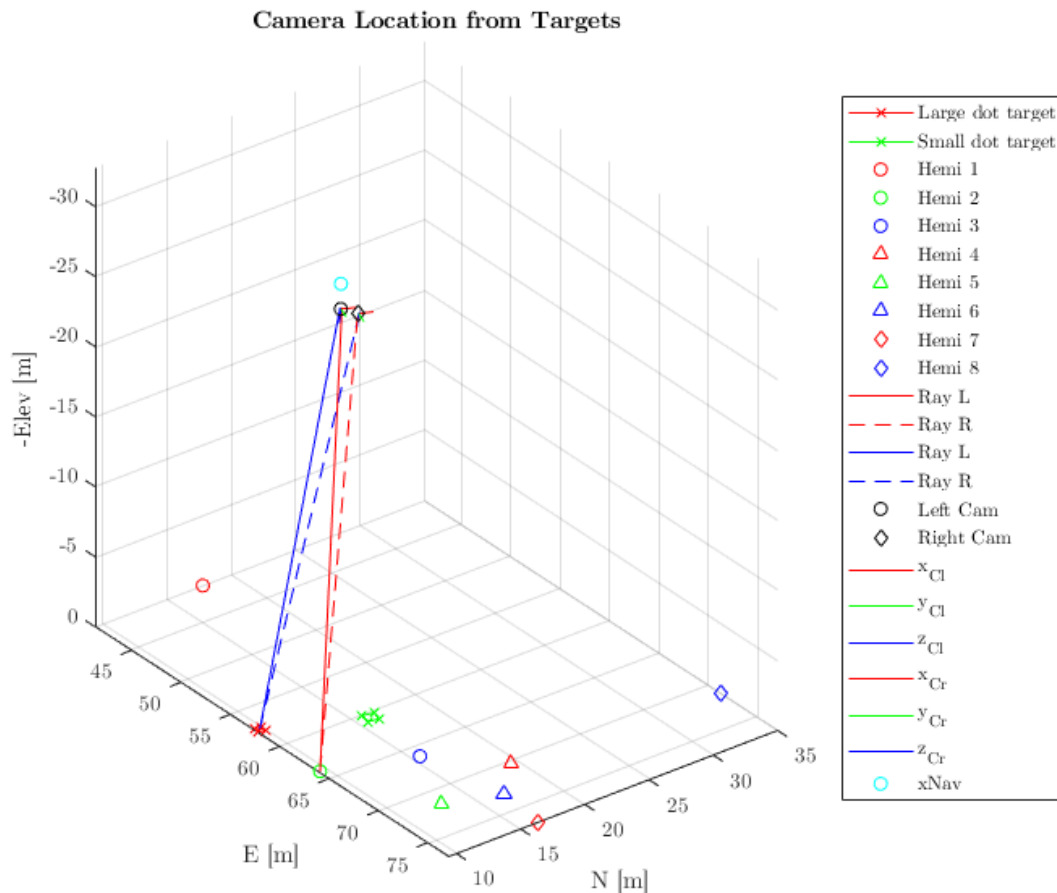
# Flight Test Overview

- Cameras mounted coaxially at 1.71 m baseline on the struts of an ASTAR AS350B3E helicopter
  - 1Hz synchronized imaging triggered by GPS 1PPS
- Dual GPS antennas mounted on aft and forward cross-tubes
- xNav 550 secured to helicopter floor
- 2x operators in helicopter back seat
  - Recording start/stop, exposure time adjustment, xNav 550 GNSS/INS convergence monitoring, ground comms
- Images taken in vicinity of Pisgah lava flows, CA
- Hemispherical hazard mounts and calibration targets placed at surveyed locations on ground
- 11x ascent/descent image sequences recorded with varied terrain and lighting conditions



# GPS Elevation Bias Removal

- Surveyed targets, with known location, were imaged at low altitudes
- Pixel locations of targets provided a bearing vector from target to camera
- Camera location triangulated
- GPS bias corrected for when calculating ground truth altitude



# Flight Test Calibration

- Camera pointing directions unknown due to ~10-20 Hz camera vibration
  - Flight implementation needs a rigid bar between cameras

## *Initial Intrinsic Calibration:*

- Used ground test surveyed monocular calibration

## *Initial Extrinsic Calibration:*

- Translation magnitude measured using Leica Total Station rangefinder
- Camera orientation determined individually for each image pair
  - Natural SIFT features detected and matched between left and right images
  - Reprojection and depth errors of triangulated features minimized
    - Required use of GPS altitude and assumed planar ground

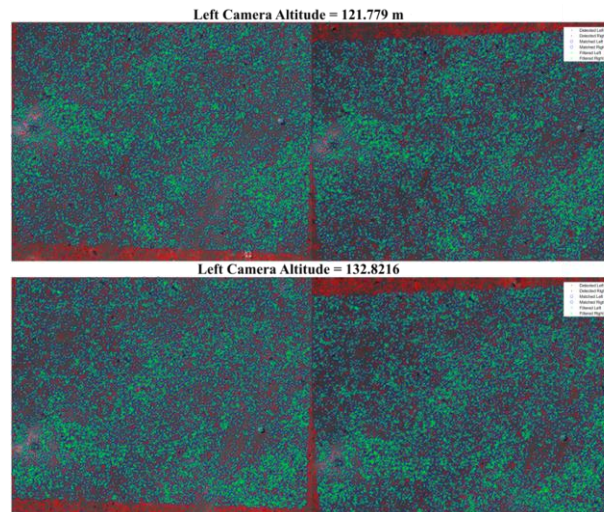
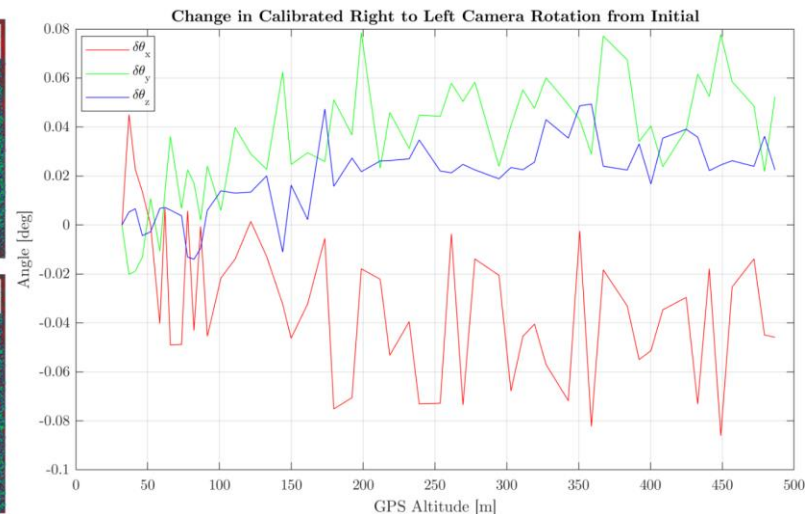


Image Pairs with SIFT Features.

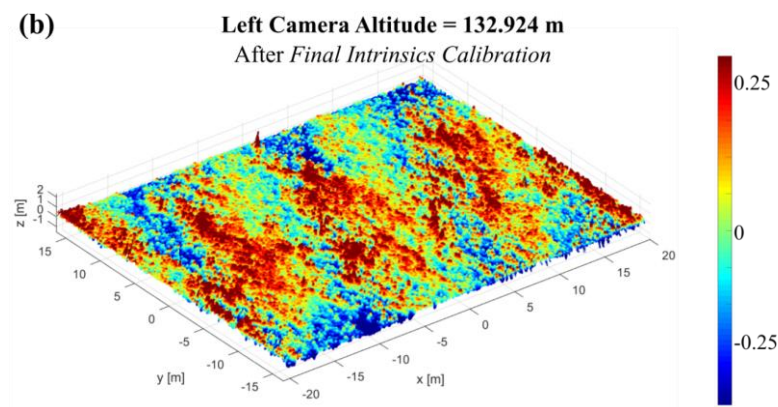
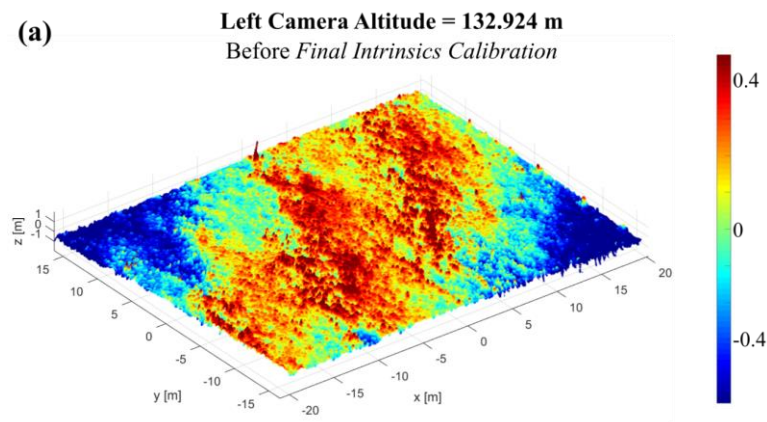


Right to Left Camera Rotation Change.

# Flight Test Calibration and Error Model

## *Final Intrinsic Calibration:*

- Surveyed monocular calibration taken at  $< 10$  m
- Flight stereo images taken at 30-500 m
- Intrinsic calibration refined for optimal ground planarity of processed flight data



## *Final Extrinsic Calibration:*

- Extrinsic calibration performed once more with final camera intrinsics

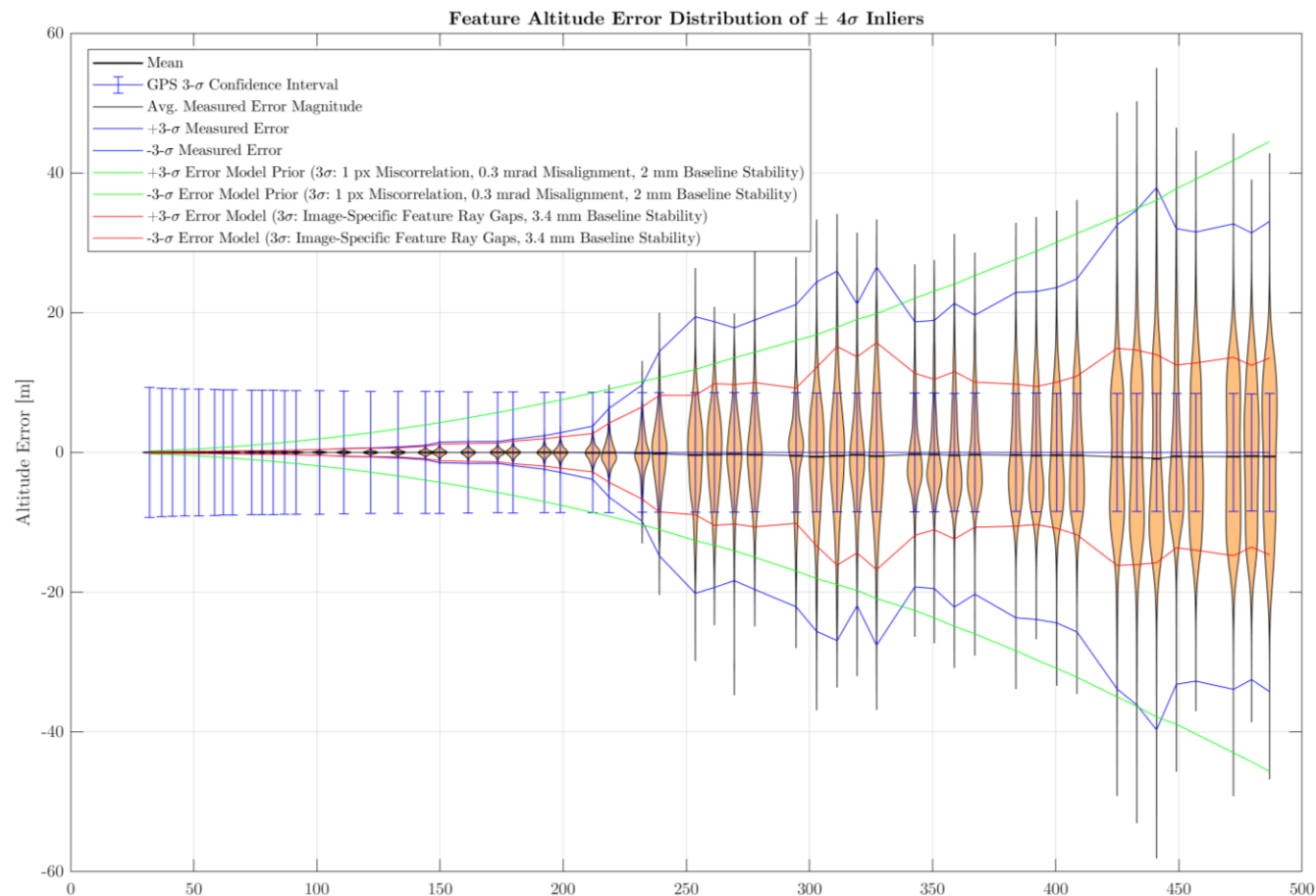
## Error Model

Stereo baseline	Camera horizontal field of view	Horizontal resolution	Correlation accuracy ( $3\text{-}\sigma$ )	Misalignment between cameras ( $3\text{-}\sigma$ )	Baseline stability ( $3\text{-}\sigma$ )
1.71 m	0.325 rad (18.6°)	2592 pixels	1 pixel	0.0003 rad (2.4 px)	0.002 m

# Flight Test Results – Feature Variance

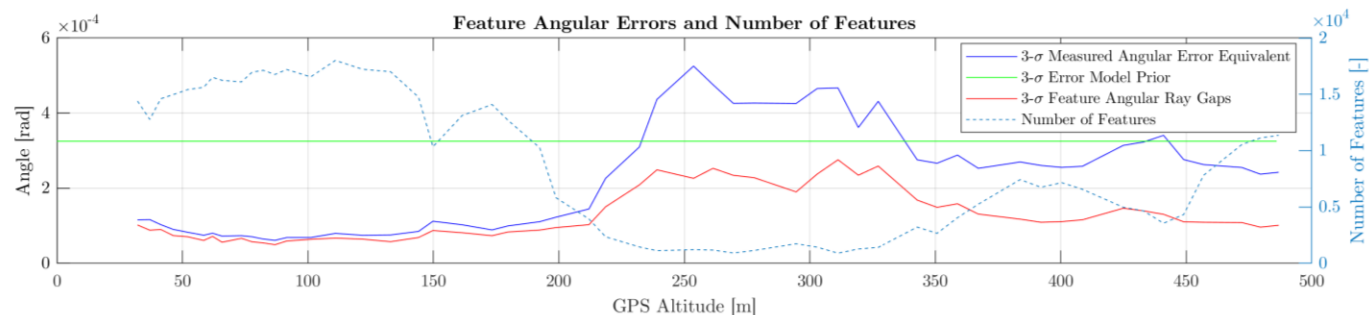
## Altitude Error

- Orange shape
  - Point distribution
- Blue trace
  - $\pm 3\sigma$  error
- Green trace
  - $\pm 3\sigma$  model



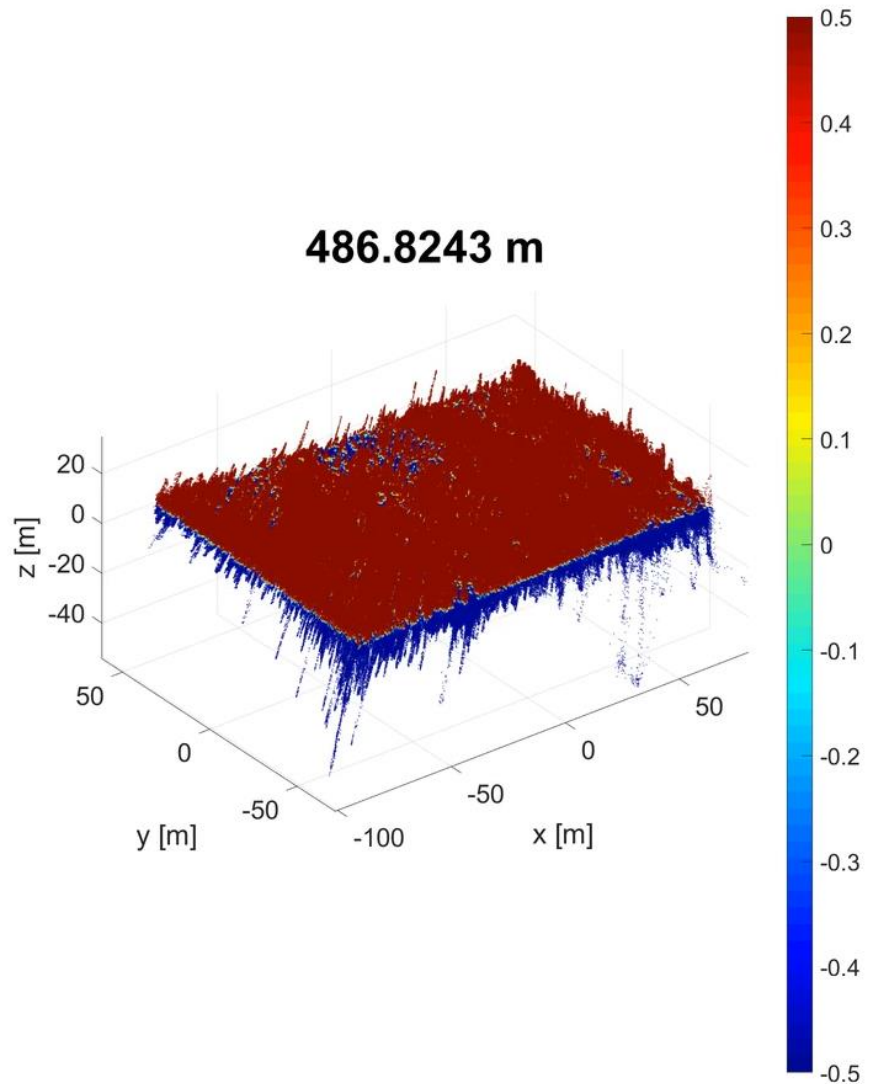
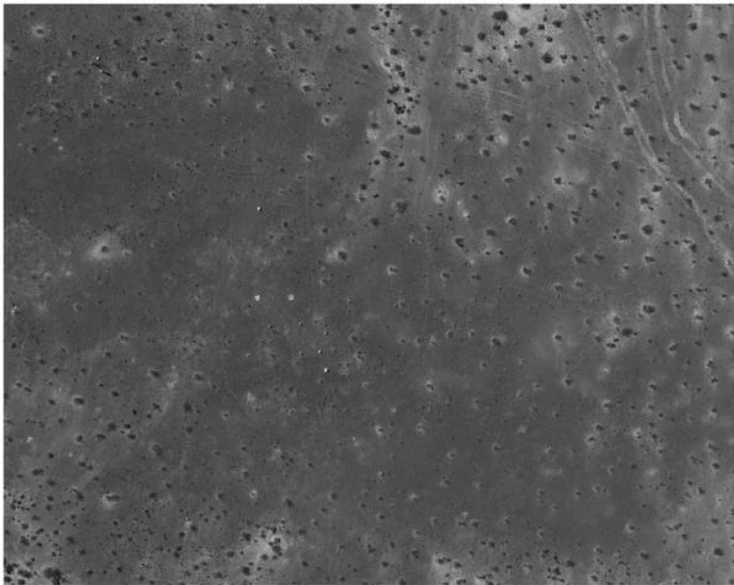
## Angular Ray Gaps

- Green trace
  - $\pm 3\sigma$  model
- Red trace
  - $\pm 3\sigma$  reprojection ray gap
- Dashed blue trace
  - # of features



# Flight Test Results – Dense Depth

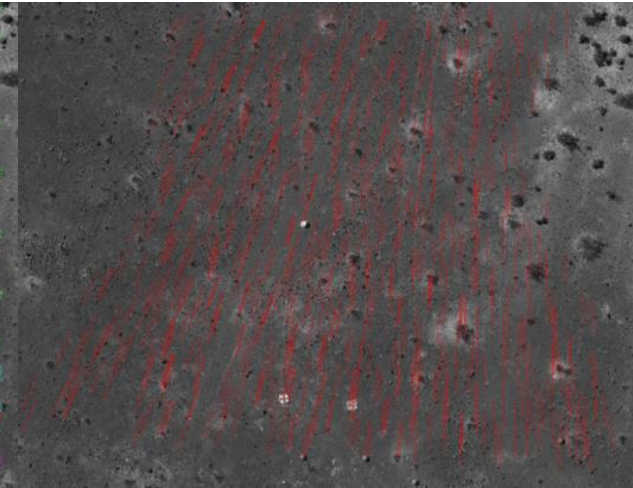
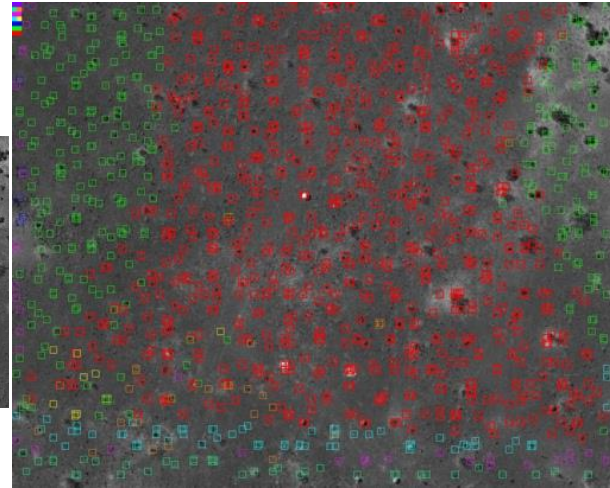
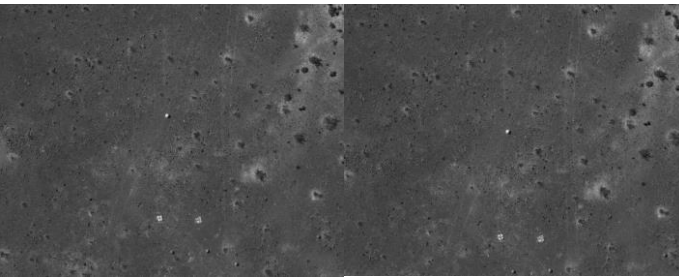
- Terrain maps summary 487 m  $\rightarrow$  32 m



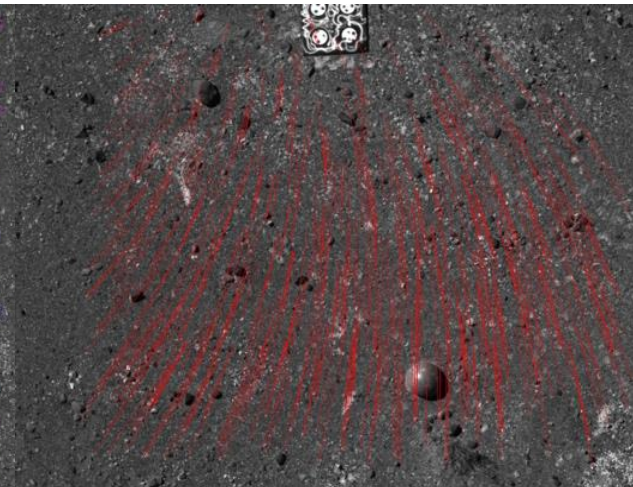
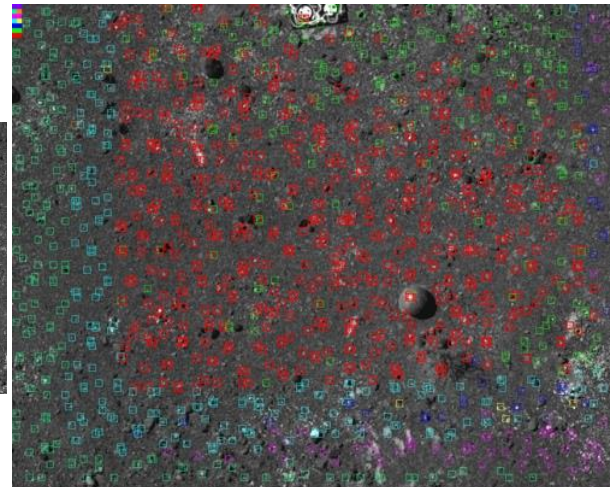
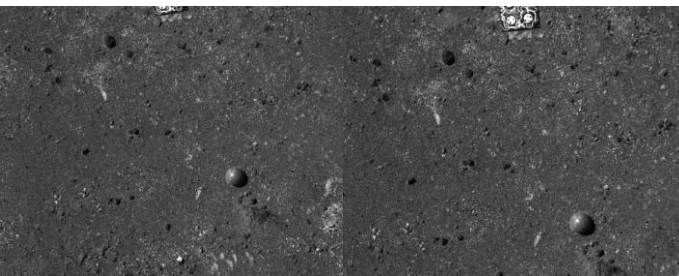
# Flight Test Results – Visual Odometry

- Visual odometry was performed using Mars Science Laboratory software
- Image sequence from 199 m → 37 m processed at 1024×1296 px (downsampled)

199 m → 192 m



37 m → 32 m



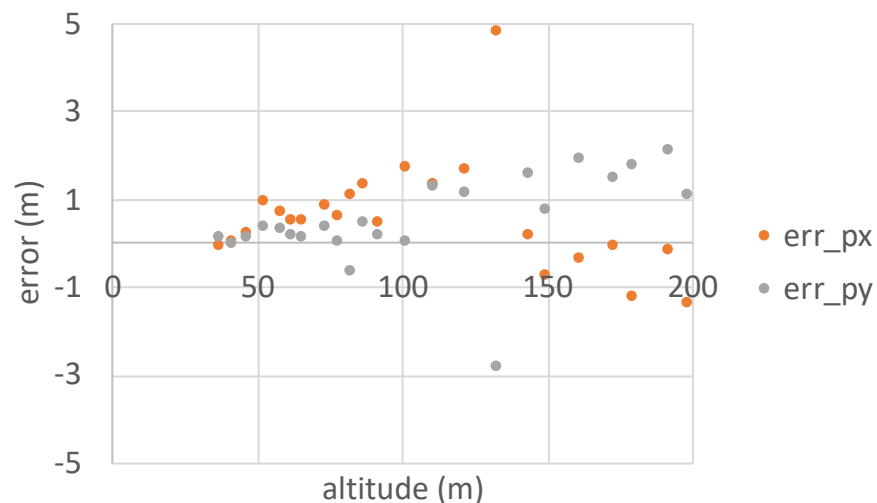
Feature outlier rejection

Feature tracks

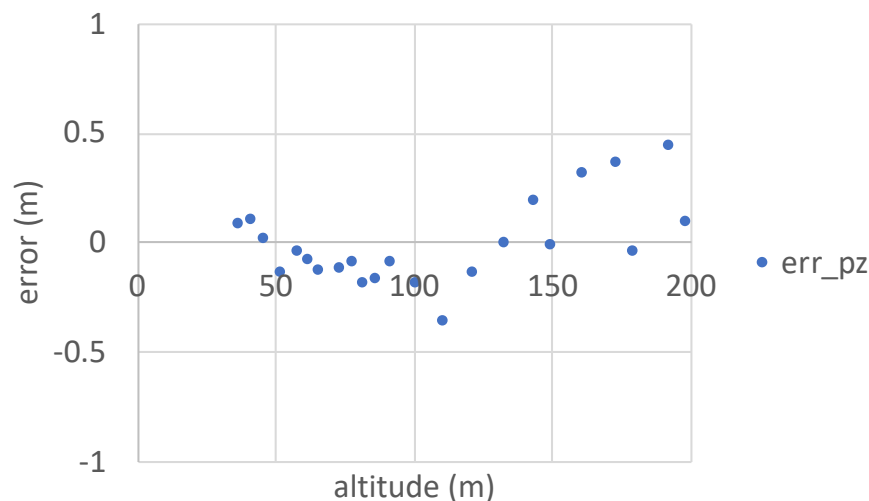
# Flight Test Results – Visual Odometry

- Visual odometry calculated translation compared with GPS-derived ground truth
- Motion errors much less than GPS “ground truth” 3- $\sigma$  uncertainty of  $\pm 6$  m
- Error at lowest altitude (37 m) is [0.08, 0.12, 0.09] m from 1 Hz data
  - Horizontal velocity measurement error of 14 cm/s
  - Vertical velocity measurement error of 9 cm/s
  - Low enough for soft touchdown for most planetary landing missions

Horizontal Motion Error



Vertical Motion Error



# Conclusions

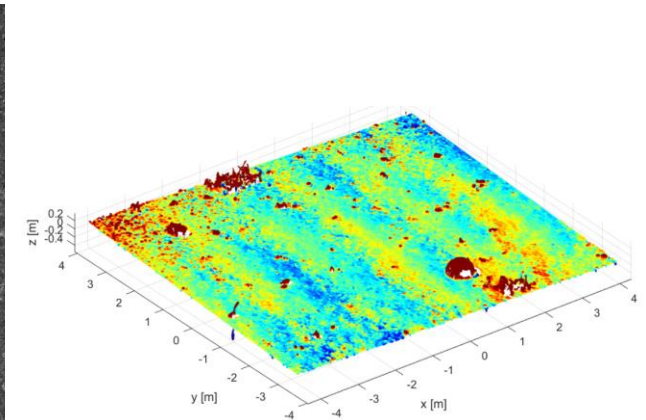
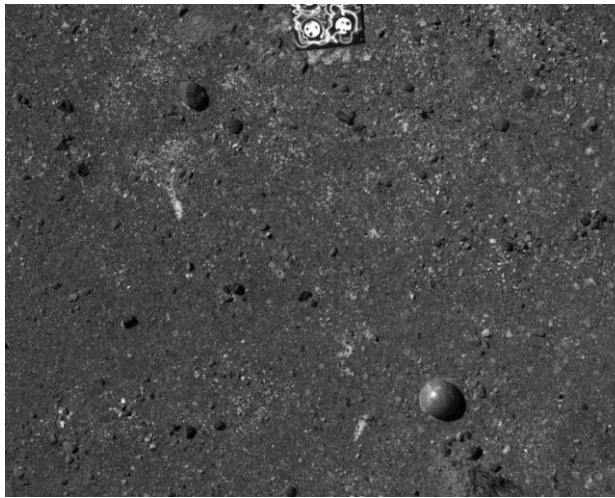
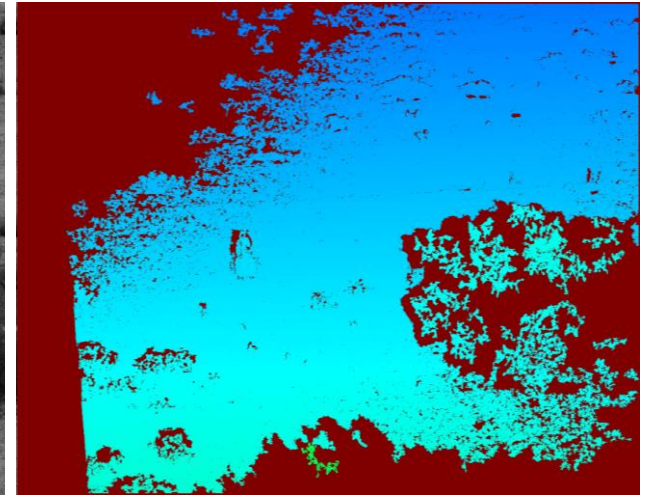
- Final landing phase requires knowledge of *altitude* and *velocity*
- Wide baseline (~2 m) stereo vision is a viable replacement for radar to sense:
  - *Altitude* at  $< 1\%$  error from altitudes of 500 m  $\rightarrow$  30 m
  - Horizontal and vertical *velocity* on order of 10 cm/s at ~40 m altitude
- For some landing missions, wide-baseline stereo vision is a viable sensor for soft landing
  - Potential use cases include landing on Ceres, the Moon, Phobos, and other small bodies
  - Need high performance computing for stereo matching
    - e.g. Vision Compute Element on Mars 2020

# References

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# Thank You

## *Questions?*





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